Determining Holocene Uplift Rates on the San Joaquin Hills Blind Thrust

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ABSTRACT *Identification of the Problem*

Realistic rupture scenarios determined for earthquakes that occur on blind thrusts in the Los Angeles basin are based on slip rates determined from uplift of well-dated Holocene strata (Shaw and Suppe, 1996; Dolan et al., 2003; Leon et al., 2010). The San Joaquin Hills, a 38 km-long anticline, formed above a west-dipping blind thrust poses significant risk for much of coastal Orange County, based on evidence for recent uplift of marine terraces (Grant et al., 1999), folding of alluvial gravels (Sundermann and Mueller, 2001) and historical accounts (Grant et al., 2002). Our work was focused on determining whether the rate of uplift as defined from the Marine Stage 5 terrace preserved on Newport Mesa is consistent with folding of much younger (Holocene) fluvial deposits preserved in the region. Results of our work suggest that much of the 5km wide, north-facing flank of Newport Mesa is actively folded above a blind thrust. Holocene deposits penetrated by CPT borings are uplifted < 1m. We interpret this as evidence for active folding above the San Joaquin Hills blind thrust during the Holocene. Our borings do not extend across the entire NE facing limb of the anticline, thus the displacement we measured is a minimum.

Methods We used cone penetrometer tests to define the amount of Holocene uplift across a part of the east dipping forelimb of the San Joaquin anticline in Irvine, in Orange County, CA (Figure 1). The anticline has been previously shown to deform a well-preserved flight of marine terraces (Grant et al., 1999). Preliminary work at CU-Boulder included mapping of subsurface aquifers using water wells to approximately locate the zone of uplift on the forelimb of the fold. In addition, we used uplift measured on Late Quaternary gravels (i.e. < 330Ka - Marine Stage 9) to estimate a long-term uplift rate across the fold (at least 0.12mm/yr). The Latest Quaternary rate of uplift of the San Joaquin Hills defined by U-Series dating of the Marine Stage 5 terrace platforms on Newport and Huntington Mesa (Grant et al., 1999) ranges from 0.21- 0.27mm/yr.

We used an in-house 20-ton CPT rig, operated by the USGS in Menlo Park to complete a boring transect across the forelimb of the anticline. A cross section of CPT borings is shown in Figures 4, 5; see map of borings on Figure 3). The CPT sensor recorded the strength of the sediment to piercing, frictional resistance to sliding and S-wave interval velocity. Correlation of strata was based on log character, in particular Fs/Qc. The elevation of boreholes was determined by surveying; selection of individual boreholes was dictated by the location of buried utilities, railroad crossings and the I-405 freeway. We acquired a set of 14 borings that ranged from 15-30 meters in depth. Well logs for all CPT borings are shown in the appendix.

Late Quaternary Stratigraphy Strata defined in the CPT profiles correlate well with existing mapping and water wells (Sprotte, 1976). Two sequence stratigraphic units were defined by the borings, including a Holocene sequence that is a finer-grained age equivalent of the Talbert Aquifer. These deposits are also consistent with the mapped location of peat-rich Holocene strata defined by (Evans, 1979). The Holocene unit is observed as gravel, sand and mud in the CPT borings, and are onlapped onto the forelimb of the anticline across a distance of ~35-40 m. The lower contact of the Holocene sequence is defined as an unconformity – based on the change in s-wave velocity - considered a good indicator of the contact in this region. Pleistocene sediment rarely has velocities below 250 m/s unless it is extremely fine-grained. Strata penetrated below the unconformity are interpreted to be strata capping the Marine Stage 5a, or 5e terraces (~78-123Ka). The age of the Holocene sequence is interpreted to be 12 Ka and younger, based on its stratigraphic position relative to the well dated Talbert Aquifer, deposited in the adjacent modern floodplain of the adjacent Santa Ana River, incised across Newport Mesa. This unit records abrupt sea level rise at the start of the Holocene, and resulting aggradation of river channels in the Los Angeles Basin.

As seen in the CPT profile, KM 26 spuds in undivided "old paralic deposits" (late to middle Pleistocene), whereas north of KM 26 the surficial unit between KM 23 and KM 22 is mapped as "young axial channel deposits" (Holocene and late Pleistocene) of the Santa Ana River, and then "young alluvial fan deposits" (Holocene and late Pleistocene) north of KM 22. In this context the two younger units distinguish locally derived materials (from the Pleistocene terraces) from the complex fan complex of the Santa Ana River. The contact that defines the base of the Holocene sequence can be projected to the surface, where it is in good agreement with mapping by Morton and Miller (2006) (Santa Ana/San Bernardino 100K geologic map). According to that mapping, KM 26 spuds in undivided "old paralic deposits" (Late to Middle Pleistocene), whereas north of KM 26 the surficial unit between KM 23 and KM 22 is mapped as "young axial channel deposits" (Holocene and late Pleistocene), and then "young alluvial fan deposits" (Holocene and late Pleistocene) north of KM 22.

Geomorphology of CPT Boring Transect - Incised Channels The geomorphology of the area of the CPT borings is dominated by the 800m wide channel of the Santa Ana River (Figure 1). The Talbert is largely contained within the modern floodplain of the river where it is incised into the Stage 5 terrace platform. This implies that the incised channel has been located in its current position for at least the last 12 Ka (based on the age of the Talbert). Given it is deposited across the forelimb of the fold, these strata offer an opportunity to measure deformation across it.

Erosion of Newport Mesa at smaller scales is marked as follows. A pair of drainage channel networks has been developed on the forelimb of the anticline (the structure we studied). The channel network towards the north, (where the CPT transect is located) drains towards the Santa Ana River (and suggests ~ 2m of incision in the channel where it is crossed by the CPT profile. The southern margin of the channel network is bounded by the forelimb of the anticline; one lower order channel is incised into the Stage 5 terrace. The other channel network drains into Newport Bay, except where it is folded across the forelimb of the fold, and the channel drains north, into a closed basin ~ 1km wide.

Folding of Newport Mesa and Late Quaternary Strata The geomorphology of the Newport Mesa marine terrace offers important constraints on the location and style of folding across the anticline. Newport Mesa is folded into an east-dipping surface, one that displays ~ 30 meters of relief. The western edge of the terrace is defined by a former sea cliff, interpreted as the Marine Stage 5c, or more likely, 5a strandline.

Strata defined in our boring profiles, regional stratigraphy seen in water wells and age dating of marine terraces are consistent with the following. Newport Mesa is a well-preserved marine terrace platform that is 123 Ka in age. The surface has been gently folded such that it dips north, and preserves the region across which shear is occurring above the San Joaquin blind thrust at depth. The portion of Newport Mesa undergoing shear above the blind thrust lies adjacent to folding of the 330 Ka Marine Stage 9 terrace, towards the southeast along the base of the San Joaquin Hills. Deformation of marine terraces in the northern San Joaquin Hills is thus consistent with the growth of an east-directed fault-propagation fold as proposed by Grant et al (1999). Relief across the fold limb (the topographic difference between the crest of Newport Mesa and it's base, where the CPT profile is located) is 29 m. Given an age of 123 Ka for the terrace surface, this translates to an uplift rate of 0.24 mm/yr, in good agreement with estimates by Grant et al, (1991) for the elevation of the Marine Stage 5e terrace preserved on the eastern side of Newport Bay. Regional uplift along the Pacific Coast (Mueller et al., 2010) that indicates 0.14 mm/yr of surface uplift is thus not evident at the latitude of the San Joaquin Hills, consistent with the long-term history of subsidence in the Los Angeles Basin.

Comparison of the San Joaquin Hills anticline with numerous examples of other fault-propagation folds in fold belts (Allmendinger, 1998; Allmendinger and Shaw, 2000; Champion et al., 2001) suggests the following. The forelimb of the anticline is ~ 5km wide. Given a range of angles subtended by the limb (the so-called apical angle, which usually are not greater than 45^o), the thrust tip is likely located at a depth of a similar amount (e.g. 5 km). Although the width of active uplift above the forelimbs of fault propagation folds decrease in concert with upward propagation of the fault tip (assuming an unchanging apical angle), the unique age of the folded marine terrace that forms Newport Mesa (78 $\pm$ < 1Ka)) must have formed in a short interval, too short for significant upward propagation of the blind thrust. This implies that the modern strain field across the forelimb is located across the entire width of the forelimb, although the steeper base of the fold where the CPT borings are located suggest some concentration of shear in this location. Coseismic folding strain is thus likely to be distributed across a broad portion of Newport Mesa, less ~ 1m of uplift spread over a width of hundreds of meters to several kilometers.

Active Deformation along CPT transect Results of our study suggest a minor amount of folding of Holocene strata deposited along the eastern flank of Newport Mesa. While additional borings would be required to define the lateral extent of recent folding, our data suggest about 1 meter of uplift since the onset of deposition of the Talbert Aquifer (Figure 4). This is a minimum because: 1) we would expect about 4 meters of relief produced by earthquakes (based on an uplift rate of 0.25mm/yr, and 2) the folding is very likely to occur well beyond the southern limit of the boring profile (where evidence of folding is present on the 123 Ka Newport Mesa surface – see above).

In a parallel effort, we attempted to determine the amount of uplift across the anticline by comparing the modern stream gradient along the floodplain of the Santa Ana River with the downstream gradient, or dip of the unconformity at the base of the Talbert Aquifer. A decrease in the gradient along the base of the 12 Ka unconformity is consistent with ~ 4 $\pm$ 2 meters of uplift across the fold limb of the anticline. This rate of uplift is consistent with that defined for the longer period of 78 Ka, the age of the marine stage 5a terrace (0.25mm/yr), although it does not provide a useful result given uncertainties in the gradient of the river at 12 Ka.

The site chosen for our study did, however, yield useful information on deformation of Holocene strata deposited along the edge of the anticline. It also provides a minimum uplift rate across the San Joaquin Hills anticline for the Holocene (post 12 Ka) period. It did not, however, capture the full amount of uplift across the fold. We know of no data that would have indicated this prior to our work. In fact, a full characterization of folding across the forelimb of the anticline would require a drilling program costing 5-10 times the amount of funding made available for our study.

Any subsequent studies should consider targeting a site where the San Joaquin Hills anticline plunges beneath the modern floodplain of the basin. Based on the pattern of uplift of the Stage 5 terraces, such a site may exist northwest of Huntington Mesa, at Seal Beach, directly north of the Bolsa Chica Ecological Reserve - where the tip of the anticline is covered by sediments of the modern coastal plain. The forelimb of the fold across Huntington Mesa is about half its width at Newport Mesa. While fewer borings would be required to characterize recent uplift at this site, a robust test would still require closely spaced borings over a distance of several kilometers, in addition to control on the age of folded sediments.

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Sprotte, 1976, Orange County Water Resources Bulletin, water well map of the Talbert aquifer between Huntington and Newport Mesas.

Well logs of all CPT borings are available by contacting Mueller at CU-Boulder.

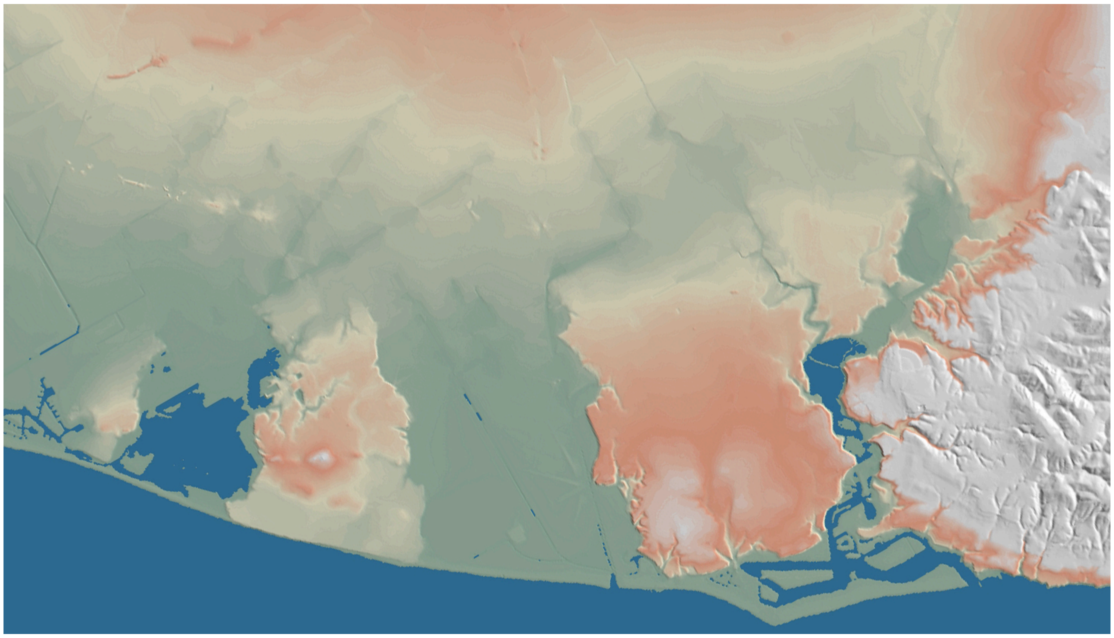

Figure 1. Detailed shaded relief map of the San Joaquin Hills anticline. Note dipping flank of Newport Mesa at right-center, gentle gradient of the floodplain of the Santa Ana river channel, and Santa Ana fan, located at the top of the image. The left center of the image shows the northern termination of the anticline near Seal Beach. Huntington Mesa is located left of Santa Ana River channel, smaller superposed structure is local uplift on the Newport Inglewood fault.

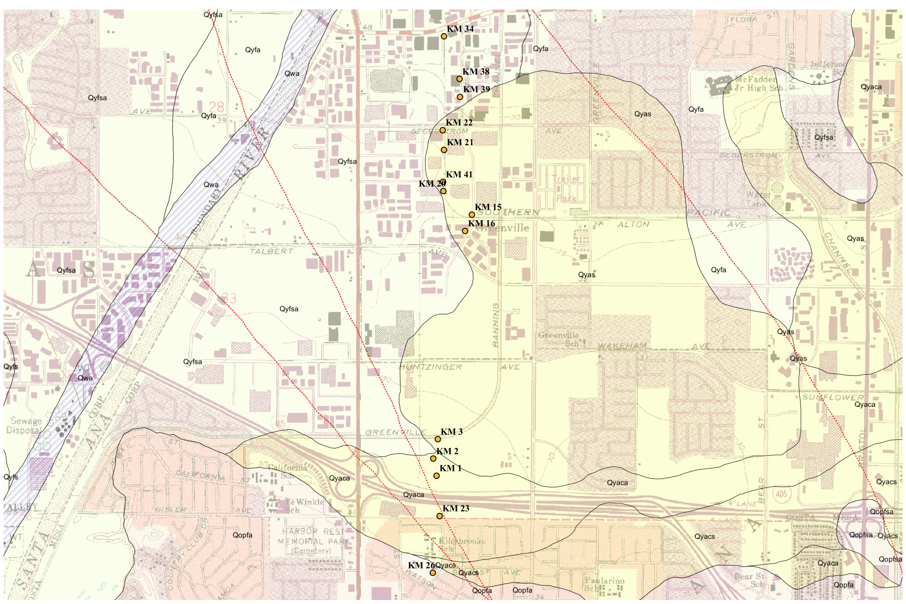

Figure 2. Location map of CPT borings.

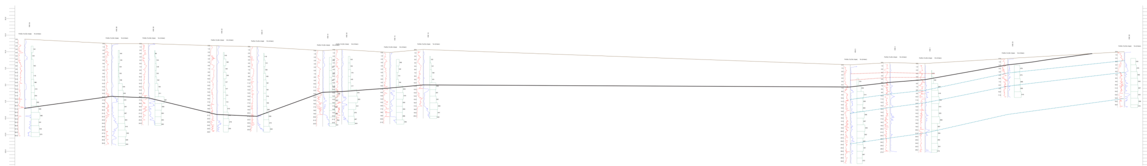

Figure 3 Entire CPT profile. See locations of borings in Figure 3 and detailed portions of CPT profile in subsequent figures. Contact is base of Holocene strata, see detailed part of cross section for additional correlations between individual beds.

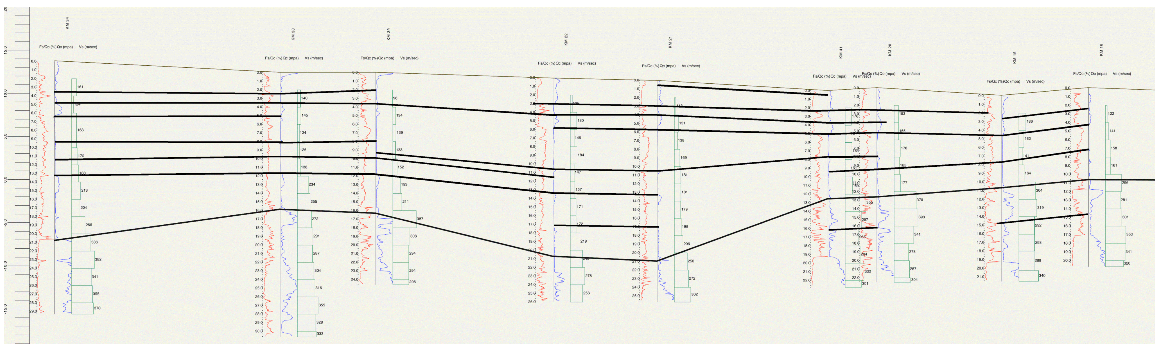

Figure 4 Details of cross section of northern set of CPT borings. Individual logs are archived in the appendix. Center wells define a buried channel, otherwise strata do not appear to be deformed.

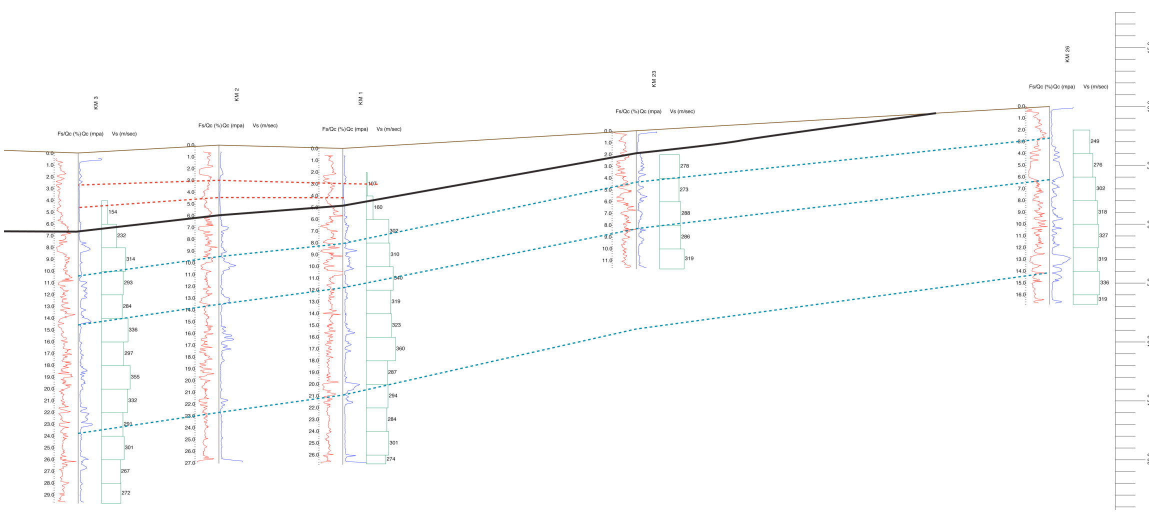

Figure 5 Details of cross section of southern set of CPT borings. Individual logs are archived in the appendix. Holocene strata equivalent to the 12 Ka Talbert Aquifer are shown in red. These are onlapped onto deposits of Marine Stage 5 terrace; unconformity between 12 Ka and 78-123 Ka units are shown as heavy black line. Note how older deposits become nearly parallel to the ground surface, here the folded surface of the marine terrace.